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INTERACTIONS OF SUPRATHRESHOLD TASTE STIMULI [1]

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Probably everyone has some hunches on how one taste quality affects another, on how sugar affects the taste of salt, on how acid affects the perception of bitterness, and the like, but many of these assertions are contradictory. Probably some of this disagreement is due to people's confusing changes in intensity of the individual taste qualities with the more ambiguous tastes created by the addition of one unitary taste stimulus to another. Thus, it may be that a salt-and-sugar solution produces relatively unclear taste sensations even though the individual qualities, when observed with a more analytic set, have the same subjective intensities as they would have in a pure salt or pure sugar solution.

No systematic investigation of taste interactions at suprathreshold stimulus intensities has ever been reported. Anderson (1950) has presented a critical review of the literature and the results of his own systematic study on interactions among stimuli at near-threshold concentrations. Fabian and Blum (1943) have summarized the early literature on taste interactions and reported their investigation of interactions between various sweet, salty, and sour substances; however, their emphasis was on the effect of a subthreshold concentration of one substance upon the perceived intensity of a suprathreshold concentration of another. They concluded that a subthreshold concentration of salt (NaCl) increased the intensity of five different sugars and reduced the sourness of five organic acids and one inorganic, hydrochloric acid (HCl). Each subthreshold concentration of the five sugars, in turn, reduced saltiness of NaCl and the sourness of the six acids. All organic acids enhanced saltiness, although HCl appeared to have no effect; but the effect of acids upon sweetness seemed to be in part a function of the specific acids and the specific sugars used. For example, the sweetness of fructose was reduced by lactic, tartaric, acetic, and malic acids; but HCl and citric acid had no effect. In contrast, citric, lactic, and tartaric acids enhanced the sweetness of sucrose, but HCl and acetic acid seemed to have no effect.

More recently, Beebe-Center, Rogers, Atkinson, and O'Connell (1959) have reported on the interactions between suprathreshold concentrations of NaCl and sucrose. Their major conclusion was that some enhancement of sweetness by salt was evident in the case of weak solutions, but the principal effect was one of masking.

For the purposes of the present study, we assumed the existence of four basic taste qualities—salt, sweet, sour, and bitter—and that the appropriate stimulus for each is NaCl, sucrose, citric acid, and caffeine, respectively. The interactions investigated were those between every pair of qualities. In each such pair, a given stimulus was studied both as to its effect on another and how it was affected by the other. Thus, mixtures of sucrose and NaCl were examined from two points of view: the effect of sucrose (secondary stimulus) upon the perceived intensity of the saltiness of NaCl (primary stimulus); and conversely, the effect of NaCl (now the secondary stimulus) upon the perceived intensity of sweetness of sucrose (now the pri-

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TABLE 1

PERCENTAGE CONCENTRATIONS OF SOLUTIONS USED IN STUDY OF INTERACTIONS OF TASTE QUALITIES

Taste Quality	Primary Series (Rated for Intensity)				Secondary Series (Added to Solutions)			
Salt (NaCl)	.15	.45	1.40	4.00	.00	.13	.44	1.50
Bitter (caffeine)	.031	.076	.195	.500	.00	.025	.048	.093
Sweet (sucrose)	.50	1.70	5.80	20.0	.00	.45	1.90	8.00
Sour (citric acid)	.009	.029	.089	.274	.00	.007	.023	.073

Note.—Concentrations represent weight of stimulus per 100 ml. of solution. Concentrations of citric acid have been corrected for the one molecule of water of crystallization. An exception occurred in the experiment on the effect of sucrose on saltiness. The NaCl concentrations were .10, .35, 1.20, and 4.00; and the sucrose concentrations were .00, .45, 1.70, and 6.00. This interaction experiment was the first one conducted, and the concentrations were slightly revised for the subsequent ones.

mary stimulus). In all, 12 sets of interactions are possible.

METHOD

Taste solutions.—Two series of each stimulus were prepared, a primary ("effect on") and a secondary ("effect of"). The concentrations in the primary series were intended to cover the range of intensities from barely perceptible to almost extreme. The concentrations in the secondary series were intended to result in perceived intensities from none to moderate, since it was thought that interaction effects would be most easily demonstrated if the four concentrations of the secondary series were of generally lower intensity than the primary series. Selections of the specific concentrations within these ranges were based upon previous unpublished data.

All concentrations are shown in Table 1 and represent the number of grams of the solute per 100 ml. of solution. The weights for citric acid have been corrected for the one molecule of water of crystallization per citric acid molecule. It will be noted that, apart from the 0% concentrations of the secondary stimulus, the concentrations in both series are approximately logarithmically spaced. The sucrose and citric acid were Merck Reagent, the NaCl was Merck C. P., and the caffeine was Pfizer U. S. P. Charcoal-filtered distilled water was always used as the solvent.

In each interaction experiment, the 16 solutions consisted of each concentration in a given primary series with each concentration in one of the three remaining secondary ones (Table 1). For example, in the experiment on the effect of citric acid upon the perceived intensity of bitterness, the primary stimulus series of caffeine (.031%, .076%, .195%, .500%) is used in combination with the secondary series of citric acid (.00%, .007%, .023%, .073%), as shown in Table 2.

Experimental design.—Each interaction experiment was independently replicated, the interval between replications varying from 1 wk. to 16 mo. The basic experimental design is given in Table 2, where the experiment on the effects of citric acid upon bitterness is shown as an example.

The levels of the primary stimulus, caffeine, and the secondary stimulus, citric acid, were taken from Table 1. The 16 solutions were divided into two sets. Half the judges (*O*s) in each replication evaluated the solutions marked "O" in Table 2, while the other half evaluated the solutions marked "X."[2]

Judges.—The *O*s were selected from a pool of approximately 700 civilian and military, male and female, employees who routinely participate in preference tests of foods though

[2] The design is a half-replicate in which the interaction of the "linear" component of the primary stimulus and the "cubic" component of the secondary is confounded with Judge-Group. Quotation marks are used to indicate that these components are not linear or cubic in the quantitative sense, but rather involve comparisons between pairs of levels. Thus, the "linear" (Component I) of caffeine, when used as the primary stimulus, means that the average perceived bitterness of the eight solutions in the first two caffeine levels is compared with the average of all eight solutions in the second two levels. Similarly, the "cubic" (Component III) of caffeine compares the average perceived intensity of the eight solutions in the first and third levels with the average of the eight solutions in the second and fourth. The quadratic (Component II) is a true quadratic and involves comparing the middle two levels against the lowest and highest ones.

TABLE 2

EXPERIMENTAL DESIGN EXAMPLE: EFFECTS OF CITRIC ACID UPON THE PERCEIVED INTENSITY OF BITTERNESS

Levels of Citric Acid (Secondary Stimulus)	Levels of Caffeine (Primary Stimulus)			
	A .031%	B .076%	C .195%	D .500%
I-.00%	X	X	O	O
II-.007%	O	O	X	X
III-.023%	X	X	O	O
IV-.073%	O	O	X	X

Note.—Solutions marked "X" were evaluated by half the *O*s, and the solutions marked "O" were evaluated by the other half. Thus, the interaction of the "linear" component of caffeine and the "cubic" component of citric acid are confounded with Judge-Group.

rarely in psychophysical investigations. Independent selections of 40 *O*s were made from the pool for each replication of each experiment. Departures from randomness occurred when some were absent or were otherwise not available on the days the tests were conducted. Because 960 persons were required (12 interactions × 40 *O*s × 2 replications) and because replacement into the pool followed selection, some *O*s participated in more than one experiment or replication.

Psychophysical method.—The single stimulus method was used with a nine-interval rating of intensity. Alternate intervals were anchored with the following descriptions of intensity: *none, slight, moderate, strong,* and *extreme.* The intervals were assigned successive integers from 1 (*none*) to 9 (*extreme*) and the ratings then treated quantitatively. The *O*s were instructed to rate the intensity of the quality represented by the primary stimulus, ignoring other qualities that might be present. They were told not to swallow the samples.

Fresh solutions were prepared for each replication session. A session was usually completed in 1 day although occasionally 2 consecutive days were needed to test the 40 *O*s. Each *O* sat in a semi-enclosed testing booth. They were presented one at a time with 6-ml. samples in coded 1-oz. glasses through a turntable in a wall separating the booth from the serving area. After rating each sample, *O* rinsed his mouth ad lib. with charcoal-filtered distilled water. The time between the rating of one solution and the presentation of the next was 30 sec. During the course of the experiments, the question arose as to whether these untrained and unscreened *O*s were aware of the characteristics of a sour or bitter substance and the distinctions between them. It was decided that on the second replication of each interaction experiment, *O* would receive a reference sample of the primary stimulus prior to rating the other eight and would be asked to note carefully its flavor without rating it. The reference sample was always a pure solution of the second highest concentration of the primary stimulus. In the analyses of variance, session was a source of variation although it is a generic term that includes ordinary session variability per se, whether or not a reference sample was served, actual differences among judge groups, etc.

RESULTS

A separate analysis of variance was performed for each taste interaction. The total variation was partitioned among the following sources of variation: each orthogonal component of the primary and of the secondary stimulus, the interaction of every component of the primary with every component of the secondary stimulus, session, interaction of session with each orthogonal component and with each primary-secondary interaction, judge, and the interaction of session and solution. Each source except the last, had 1 *df*. There were 76 *df* for Judge and 532 for Judge × Solution. The .01 level was chosen as the criterion for significance.[3]

Except for those sources of variation which were confounded with Judge-Group, the error term was Judge-Solution interaction (within groups). Those sources, for which variation

[3] Four tables showing the mean ratings of each solution and one table showing the sources of variation and their corresponding *df*'s, mean squares, and levels of significance have been deposited with the American Documentation Institute. Order Document No. 6777 from ADI Auxiliary Publications Project, Photoduplication Service, Library of Congress; Washington 25, D. C., remitting in advance $1.25 for microfilm or $1.25 for photocopies. Make checks payable to: Chief Photoduplication service, Library of Congress.

among Judges (within groups) was the error term, were Session, the interaction of Component I of the secondary stimulus and Component III of the primary, and the three-factor interaction of Session × Secondary-I × Primary-III.

As would be expected, Component I of the primary stimulus was in each case significant, far beyond the .001 level. In 21 of 24 cases, Components II and III were also highly significant. Inspection of the ratings[3] shows that the major effects of increasing the primary stimulus concentrations were true linear, although significant departures did occur.[4]

Each mean was based upon 40 ratings, 20 in each of the two replications. The mean ratings of each of the 16 solutions in each interaction experiment are plotted in Fig. 1. The results and conclusions will be discussed separately for each interaction. The general error term, Judge-Solution interaction, will be indicated in parentheses.

Effects of Caffeine

Upon saltiness.—No significant effects of caffeine upon saltiness were found. Regardless of the level of caffeine, saltiness was merely a function of the salt itself. There was only a slight suggestion that if the caffeine level were increased even further, saltiness might eventually be enhanced. (Error $MS = 1.39$.)

Upon sweetness.—No variables affected sweetness other than the sucrose concentrations themselves. However, Caffeine-I was almost significant; the observed F was 6.50, compared to an F of 6.64 required for significance at the .01 level. Only a suggestion of masking by caffeine was present, the difference between the lower two and higher two caffeine concentrations being only .26 scale points. Higher levels of caffeine might demonstrate eventual masking of sweetness. (Error $MS = 1.70$.)

Upon sourness.—Components I and III of caffeine were each significant at the .001 level. Inspection of the mean intensity ratings reveals that the effect was one of enhancement, with no other significant sources of variation complicating the interpretation. (Error $MS = 2.94$.)

Effects of NaCl

Upon bitterness.—No significant effects were found, other than those attributable to caffeine. The curves were somewhat jagged and suggested a Caffeine-I×Salt-III interaction. However, the interaction of these two components was confounded with Judge-Group, and hence the variation among *O*s was used as the appropriate error term. (Both Judge-Solution and between-Judge *MS*s were unusually high, 3.68 and 9.63, respectively.) Despite the fact that the same types of curves emerged in the two replications and that there was a high mean square for the interaction, use of the large error term (between-Judge rather than Judge × Solution) worked against obtaining a significant F. In view of the magnitude of the mean square for this source of variation, a logical next step would be to replicate this entire experiment with a different set of confounding relationships, e.g., Primary-III×Secondary-II. (Error $MS = 3.68$.)

Upon sweetness.—Salt Components I and II were significant at the .01 level. This is interpreted to mean that salt generally tends to mask sweetness, and there is some curvature in the effects. The interpretation is complicated by two interactions which were also significant at the .01 level: (*a*) The first is the Salt-I × Sucrose-I interaction. For the lower sucrose concentrations, the various levels of salt had relatively little effect. Instead, the reduction of sweetness

[4] If orthogonal polynomials are used on the mean ratings (Anderson & Bancroft, 1952), it will be found that the true linear is greater than Component I, with a corresponding decrease in the mean square for the true cubic. This effect is due to the fact that although Component I is mostly linear, it does reflect some cubic; Component III, in turn, contains some linear.

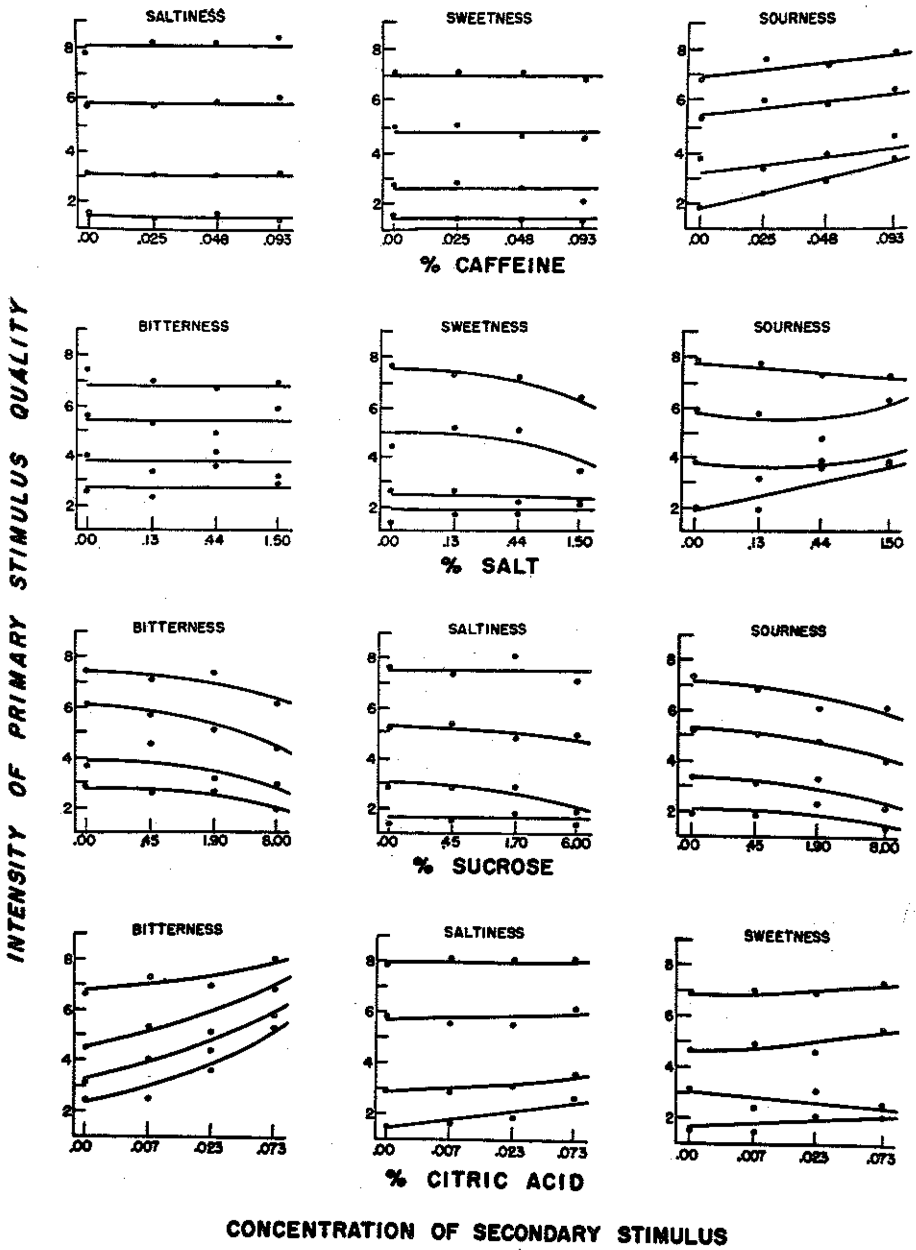

FIG. 1. Summary of taste interactions. (The abscissa represents increasing concentrations of the secondary stimulus. The four curves in each graph are for the four levels of the primary stimulus whose taste quality is shown on each graph. See Table 1 for concentrations. Curve fitting was guided by the significance of the sources of variation in the analyses of variance, rather than by least squares methods.)

occurred primarily for solutions that were high in both salt and sucrose. (*b*) The second is the Salt-II × Sucrose-I interaction. Again, for the lower sucrose concentrations, the various levels of salt had relatively little differential effect on sweetness. The greatest effect was on the higher sucrose concentrations by the highest salt concentrations, with a lesser effect by the lower salt concentrations.

In both of these interactions, the very highest salt concentration had its greatest sweetness-depressing effects at the higher sucrose concentrations. Thus, while the over-all effect of salt upon sweetness was one of masking, this did not occur or was not as pronounced for the lowest sucrose concentrations. In fact, for the very lowest sucrose, salt seemed to enhance sweetness.

The results are consistent with the conclusion of Beebe-Center et al. (1959), that some enhancement of sweetness by salt does occur although the major effect was one of masking, and with the report by Fabian and Blum (1943) that near-threshold concentrations of salt enhance sweetness.

Future research might well be devoted to more intensive study, at just above threshold salt concentrations, of sucrose concentrations between .5% and 6%, the region in which the shift from enhancing to masking appears to occur. (Error $MS = 2.24$.)

Upon sourness.—The results of this experiment are more complex than those of the others. Apart from the citric acid itself, Component-II only of salt had an effect ($P < .01$); the highest and lowest (0%) salt concentrations had less effect than the middle ones. This result, however, should be viewed in the light of the significance of two interaction terms: Salt-I × Citric Acid-I ($P < .001$); Salt-I × Citric Acid-III ($P < .01$). The latter may have arisen because Component III has some linear effects. The highest levels of salt tended to enhance the sourness of the lower concentrations of citric acid, but reduced the sourness of the higher acid concentrations.

From these two significant sources of variation, from the fact that they appeared in both sessions, from the absence of other significant effects (except between-judge variation), and from inspection of the mean ratings, we can infer that low level salt depressed sourness, but high levels enhanced it so that an over-all effect was not apparent. The higher the acid concentrations the later these two stages appear—in terms of increasing salt concentrations. Thus, .13% salt appeared to have reduced the sourness of the lowest two acid concentrations, but as the salt was increased to .44%, enhancement took place; .44% salt had a depressing effect on the highest two levels of acid, but 1.50% salt seemed to increase sourness.

No explanation of this nonmonotonic function is apparent. Quantitative chemical analyses of the solutions failed to reveal errors in making them up, nor did examination of the ratios of the normality of the salt to the normality of the acid suggest a chemical explanation. What is needed is an extended range of salt, a more detailed study of the points around the minimum sourness intensities produced by salt at each citric acid concentration, and use of other acids as sour stimuli. (Error $MS = 2.74$.)

Effects of Sucrose

Upon bitterness.—Sucrose reduced the intensity of bitterness. Component I was significant at the .001 level, while Components II and III were significant at the .01 level. Although successively increasing sucrose concentrations consistently reduced bitterness, the highest concentration seemed to have a disproportionately large effect.

Two solutions (.45% sucrose, .076% caffeine; 1.9% sucrose, .50% caffeine) appeared to deviate somewhat from the downward trend. The significance ($P < .001$) of the Primary-III × Secondary-III × Session interaction largely reflects this deviancy and the fact that it occurred for only one session. Hence, its bearing on the major conclusion is negligible.

The Caffeine-I × Session interaction was also significant ($P < .001$), and was due to the fact that *O*s in Session 1 did not use the upper categories of the rating scale as often as did *O*s in Session 2; thus, the range of their average ratings was lower. This phenomenon, commonly appearing during psychophysical tests, is not considered important.

Except for the two deviant solutions on one session, the effects of sucrose were fairly clear-cut—sucrose reduced bitterness. (Error $MS = 2.74$.)

Upon saltiness.—Sucrose had no general enhancing or masking effects on saltiness, a result in agreement with that reported by Beebe-Center et al. (1959). Also in agreement was the indication that the relationship might be somewhat complex. Thus, the interaction of Salt-III with Sucrose-III was significant ($P<.01$); and inspection of the mean ratings suggests that this may be attributable to the highest sucrose concentration (and to a lesser extent, the next-to-lowest sucrose concentration) rather sharply reducing the saltiness of the highest and next-to-the-lowest salt concentrations. Why this effect did not occur for the second highest salt concentration is not readily apparent.

The Salt-II × Sucrose-I interaction was also significant ($P < .01$), but this effect seemed to occur primarily for one session. Because the triple interaction involving Session was also significant ($P < .001$), not much importance is attributed to the significance of the simple interaction.

Apart from the absence of over-all enhancing or masking effects, the results of this experiment are not as definitive as those of the others. Further research should be devoted not only in replicating this one, but should also extend the sucrose concentrations to perhaps 15 or 20%. (Error $MS = 1.69$.)

Upon sourness.—All three components of sucrose were significant, Component II at the .01 level and the others at the .001 level. Sucrose reduced the intensity of sourness, a result in general agreement with that reported by Fabian and Blum (1943) and those cited by them. The sharpest drop in intensity occurred for the 6.00% sucrose concentration. If the range of sucrose concentrations were extended, the masking effects would probably be even more pronounced. (Error $MS = 2.60$.)

Effects of Citric Acid

Upon bitterness.—Citric acid very markedly enhanced bitterness, as is demonstrated by the significance of all three components, I and III at the .001 level, Component II at the .01 level. The steepest rise in bitterness was evident between the highest and next highest citric acid concentrations. The Citric Acid-I × Caffeine-I interaction was also significant ($P < .001$). The acid had a proportionately greater effect upon the lower concentrations of caffeine than on the higher concentrations. This effect may be partly at least due to restriction of the rating scale at the highest caffeine concentrations.

The Caffeine-I × Session interaction was also significant ($P < .001$). In Session 2, *O*s used a narrower range in evaluating the solutions. No special importance is attributed to this result.

The conclusions from this experiment are probably so clear that further study would not be as fruitful as with several of the other interactions. (Error $MS = 2.79$.)

Upon saltiness.—Saltiness was generally enhanced by citric acid, as shown by the significance ($P < .001$) of the Citric Acid-I component. The enhancement has not been shown to be dependent upon the level of salt. The absolute increase was not very marked, being only .32 scale points between the lowest two and highest two citric acid concentrations; but, the error term is the lowest of all interaction experiments.

Salt-I × Session interaction was also significant at the .001 level. The *O*s in Session 2 tended to restrict their range of ratings, this restriction being manifested more at the higher levels. As in the previous interaction, this finding is not of any special importance.

Extending the range of citric acid

concentrations might reveal a drop-off in enhancement, particularly for the lower salt concentrations, and perhaps an eventual masking for the higher salt concentrations. (Error $MS = 1.47$.)

Upon sweetness.—Citric acid generally increased sweetness ($P < .01$). This major conclusion is in agreement with that of Fabian and Blum (1943), who used only near-threshold concentrations of citric acid. The only other significant ($P < .01$) source of variation, Primary-I × Session, means that in Session 1, *O*s rated the solutions containing the weakest concentrations of sucrose higher than did *O*s in Session 2. Thus, the range of ratings was more restricted on Session 1 than on Session 2.

Extending the range of citric acid concentrations should aid in better defining the mathematical relationship between citric acid and perceived sweetness, particularly in determining whether the increase finally levels off and perhaps changes to a decrease. (Error $MS = 1.98$.)

Discussion

In most experiments the results were clear-cut, and the functional relationships between the primary and secondary stimuli were either monotonic or nonexistent. Where ambiguities or hints of a trend with different stimulus concentrations appeared, recommendations for follow-up research were indicated. No secondary stimulus had a uniformly enhancing or depressing effect on the remaining three primaries; nor was any primary uniformly enhanced or depressed by other secondaries. Also, what happened at near-threshold stimulus concentrations was not necessarily predictive of suprathreshold phenomena.

The general results from the "linear" comparisons may be summarized as follows: (*a*) Caffeine does not appear to affect saltiness, nor does salt appear to affect bitterness. (*b*) Caffeine does not seem to increase or decrease sweetness, but sucrose depresses the perceived intensity of bitterness. (*c*) Caffeine and citric acid have a mutually enhancing effect upon the taste quality specific to each. (*d*) Salt decreases sweetness, but sucrose does not appear to affect saltiness. (*e*) Salt seems to have no monotonic effect upon sourness, but citric acid increases saltiness. (*f*) Sucrose decreases sourness, but citric acid enhances sweetness.

Conspicuously absent from this paper is reference to physiological correlates of taste perception. The assumption that four primary taste qualities exist does not imply that four types of receptors also exist. Pfaffmann (1958), in his study of electrical recording of nerve impulses from single taste nerve fibers of the rat, was unable to find complete specificity of receptor action. For example, NaCl and sugar activated the same sensory nerve fiber and its attached sense endings. The possible afferent discharge patterns, Pfaffmann concluded, may include not only an increase but a decrease in neural flow and that the primary taste qualities represent nodal points in the manifold of taste sensations rather than basic receptor types.

The taste interactions reported here probably have a neurological basis, and the complexity of some of the results of the interaction experiments (e.g., NaCl-sucrose interactions) may reflect complex neural patterns such as those described by Pfaffmann.

The design, method, and *O*s used here were not typical of those used in most psychophysical research. One intrinsic disadvantage of the half-replicate design with specified confounding relationships is that no *O* evaluates all solutions, so that the error terms for a few sources of variation are larger than in a full factorial design and so that irregularities in curves can be attributed either to differences in the two groups or to "real" effects. Balanced against this weak point is the efficiency of the design and the single stimulus method (cf., matching method) in minimizing testing time of *O*s and in avoiding loss of motivation through testing of all solutions at one sitting. It was not feasible to have the same *O*s return to a second session to complete the ratings of the eight samples they did not test during the first.

Nevertheless, in view of suggestions of possible significance of the variable which was confounded with Judge-Group, a different confounding relationship might have proved to be more revealing.

The relative difficulty in rating—the ambiguity of the sensations—is partially reflected in the magnitude of the error terms. Saltiness seemed to be the easiest to evaluate, insofar as *O*s tended to agree more with each other on this quality than on the others. Sweetness was next lowest, but bitterness and sourness had errors of the order of twice that of saltiness. A design similar to the one used here would be too laborious to employ for interactions among three or four stimuli, but the present data should prove useful in selecting the optimum concentrations for exploring the relationships among mixtures of more than two stimuli.

Summary

Twelve experiments were conducted to determine how each unitary taste quality is affected by each of the other taste qualities. Solutions containing stimuli appropriate to both taste qualities were rated for intensity of sweetness, saltiness, sourness, or bitterness by a group of judges. Each experiment was independently replicated. In most cases, the effects were those of simple enhancement or masking, or no effect at all was found. Certain exceptions and complex relationships occurred, and recommendations for follow-up research were made. Various aspects of the method and design were discussed.

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